

Photonic Legacy in Singularity-Free Quantum Geometry: A Geometric Resolution of the Black Hole Information Paradox

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Abstract

The black hole information paradox arises from the termination of geodesics at classical spacetime singularities, leading to an apparent breakdown of unitary evolution. In this work, we investigate the fate of information within a singularity-free geometric framework. Building upon an effective quantum-corrected geometry with a fundamental minimal length scale, we demonstrate that null geodesics remain complete and energy densities finite. We propose that photons, as fundamental carriers of information, transmit information deterministically through the bounce phase of gravitational collapse. This mechanism, referred to as *photonic legacy*, provides a geometric and causal resolution of the information paradox without invoking exotic quantum postulates.

1 Introduction

The prediction of spacetime singularities within classical General Relativity leads to severe conceptual difficulties, most notably the black hole information paradox. In conventional treatments, the convergence of timelike and null geodesics at a singularity implies the irreversible loss of information, contradicting the principles of quantum mechanics.

Recent developments in singularity-free models of gravitational collapse suggest that these pathologies may arise not from fundamental physics, but from an incomplete geometric description. If spacetime admits a minimal length scale, classical singularities are replaced by regular cores, and geodesic completeness may be restored. This work explores the implications of such regular geometries for the propagation of light and the preservation of information.

2 Geodesic Completeness and Information Loss

In classical black hole interiors, null geodesics terminate at $r = 0$, rendering the evolution of massless fields ill-defined. Information loss is therefore a direct consequence of geodesic incompleteness rather than an intrinsic quantum effect.

Within a singularity-free effective geometry, the condition for information preservation reduces to a purely geometric requirement: null geodesics must remain extendable across the entire spacetime manifold. When this condition is satisfied, the propagation of light remains deterministic, and no fundamental information destruction occurs.

3 Effective Geometry and Null Propagation

We consider an effective radial coordinate of the form

$$r_{\text{eff}} = \sqrt{r^2 + \alpha^2 \ell_p^2}, \quad (1)$$

where ℓ_p is the Planck length and α is a dimensionless constant of order unity. This modification ensures that the physical area element remains finite at all radii.

The corresponding effective metric admits finite curvature invariants and preserves null geodesic completeness. In particular, the energy density associated with propagating photons remains bounded as $r \rightarrow 0$, preventing the classical divergence responsible for information loss.

4 Photonic Legacy Through the Bounce

As gravitational collapse proceeds toward the minimal radius, quantum-geometric effects induce an effective repulsive behavior, resulting in a bounce at

$$r_{\text{bounce}} \approx (\alpha \ell_p^2 M)^{1/3}. \quad (2)$$

Photons approaching the core are not destroyed but instead undergo a deterministic scattering process governed by the regular geometry. Their phase, frequency, and polarization information are preserved and redistributed into the post-bounce expanding spacetime.

We refer to this causal transmission of information across the bounce as *photonic legacy*. In this picture, information is not lost behind a singular boundary but inherited by subsequent spacetime regions through continuous null trajectories.

5 Implications for the Information Paradox

The photonic legacy mechanism reframes the black hole information paradox as a geometric artifact of singular spacetimes. When curvature divergences are removed and geodesic completeness is restored, information loss does not arise.

Importantly, this resolution does not require modifications to quantum mechanics, non-local effects, or violations of unitarity. Instead, it follows naturally from the causal structure of a regular spacetime geometry.

6 Conclusion

We have presented a geometric resolution of the black hole information paradox based on the propagation of light in singularity-free spacetimes. By demonstrating that null geodesics remain complete and photon energy densities finite, we have shown that information can be deterministically transmitted through the bounce phase of gravitational collapse.

The concept of photonic legacy provides a physically transparent and testable framework in which information is preserved without invoking speculative quantum assumptions. Future work will explore observational and cosmological implications of this mechanism.

References

- [1] S. W. Hawking, Phys. Rev. D **14**, 2460 (1976).
- [2] A. Ashtekar and M. Bojowald, Class. Quant. Grav. **22**, 3349 (2005).
- [3] L. Modesto, Class. Quant. Grav. **23**, 5587 (2006).

- [4] C. Rovelli, *Quantum Gravity*, Cambridge University Press (2004).
- [5] V. Cardoso, E. Franzin, and P. Pani, Phys. Rev. Lett. **116**, 171101 (2016).